Estimates of Percolation Rates and Ages of Water in Unsaturated Sediments at Two Mojave Desert Sites, California–Nevada

By David E. Prudic

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	Ву	To obtain
centimeter (cm)	0.3937	inch
centimeter per year (cm/yr)	0.3937	inch per year
cubic centimeter (cm ³)	0.06102	cubic inch
gram (g)	0.03527	ounce
gram per cubic centimeter (g/cm ³)	62.43	pound per cubic foot
gram per square centimeter (g/cm ²)	2.049	pound per square foot
kilogram (kg)	2.205	pound
meter (m)	3.281	foot
microgram per cubic centimeter (μg/cm ³)	0.00006243	pound per cubic foot
microgram per gram (μg/g)	0.000160	ounce per pound
icrogram per square centimeter (μg/cm²)	0.0000205	pound per square foot
milligram per kilogram (mg/kg)	0.000160	ounce per pound
milliliter (ml)	0.0002642	gallon
millimeter (mm)	0.03937	inch
pascal (Pa)	0.02089	pound per square foot

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = $[9/5(^{\circ}C)]+32$. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = $(5/9)(^{\circ}F-32)$.

Chemical concentration: Milligrams per liter approximately equal parts per million when dissolved-solids concentration is less than about 7,000 milligrams per liter.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called Sea-Level Datum of 1929), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

Estimates of Percolation Rates and Ages of Water in Unsaturated Sediments at Two Mojave Desert Sites, California–Nevada

By David E. Prudic

Abstract

Thick unsaturated zones in arid regions increasingly are being sought for the burial of radioactive and other hazardous wastes. Estimating percolation rates of water from precipitation at proposed burial sites is important for site assessment. Chloride profiles in unsaturated sediments are used to show differences and similarities in the rates of percolation at two sites in the Mojave Desert of southern Nevada and southeastern California; the first is an existing burial site for low-level radioactive waste in the Amargosa Desert, Nevada, and the second is a proposed waste-burial site in Ward Valley, California. The Mojave Desert is one of the most arid regions of the United States.

Chloride concentrations in pore water of unsaturated sediments peak between depths of 2 and 3 meters at both the Amargosa Desert and Ward Valley sites; maximum chloride concentration is 9,000 milligrams per liter at the Amargosa Desert site and 15,000 milligrams per liter at the Ward Valley site. Below a depth of 10 meters, however, chloride concentrations at the Amargosa Desert site decrease to less than 50 milligrams per liter, whereas concentrations at the Ward Valley site are greater than 2,000 milligrams per liter. Estimated age of water at a depth of 10 meters at both sites is between 16,000 and 33,000 years. Below a depth of 10 meters, water in the sediments at the Ward Valley site is estimated to be considerably older than at the Amargosa Desert site because of the greater chloride concentrations at the Ward Valley site.

The dilute chloride concentrations in the pore water below a depth of 10 meters at the Amargosa Desert site could indicate that the sediments were flushed with water in the past. The climate in the region was wetter and cooler from about 30,000 to 18,000 years ago. Perhaps increased precipitation or more frequent flooding of the Amargosa River resulted in deep percolation at the site. Downward percolation of water since that time seems limited to the upper 10 meters.

The downward percolation rate of water below a depth of 10 meters at the Amargosa Desert site as estimated from chloride concentrations, is 0.2 centimeters per year; however, the rate is not representative of present conditions, as measured water-potential and vapor-density gradients indicate upward water flow. The rate may be representative of a period during the late Pleistocene when the climate was wetter and cooler. Estimated percolation rates below a depth of 10 meters at the Ward Valley site are on the order of 3 to 5 centimeters per 1,000 years. These rates also reflect flow conditions during the late Pleistocene.

INTRODUCTION

Determining the rate and direction of water movement through thick unsaturated zones in arid regions of the United States is becoming increasingly important as sites in these regions are being sought for burial of radioactive and other hazardous wastes. Chloride concentrations in sediments can provide an estimate of long-term downward water fluxes (Allison and Hughes 1978, 1983; Allison and others, 1985;

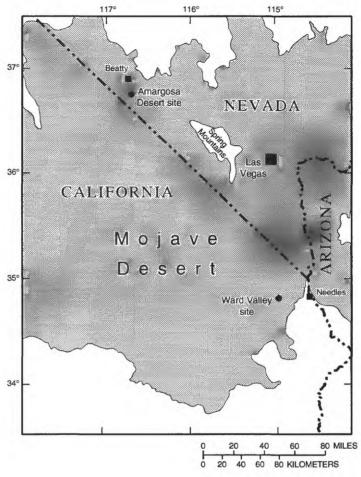


Figure 1. Location of Amargosa Desert and Ward Valley study sites in Mojave Desert of southern Nevada and southeastern California. Extent of Mojave Desert from Spaulding and others (1983, fig. 14-2).

Scanlon, 1991; Allison and others, 1994; and Phillips, 1994). Additionally, the period during which chloride has accumulated in the sediments can be estimated.

The purpose of this report is to present and compare chloride profiles, the time periods for chloride to accumulate in the sediments, and estimates of downward percolation rates (water fluxes) near a site for burial of low-level radioactive waste in the Amargosa Desert south of Beatty, Nev., and at a proposed wasteburial site in Ward Valley west of Needles, Calif. (fig. 1). Depth to ground water at the Amargosa Desert site is generally 85 to 115 m below land surface and the total thickness of unconsolidated sediments is more than 175 m (Fischer, 1992, p. 6). Depth to ground water at the Ward Valley site is generally 196 to 229 m

(Dames & Moore, 1991, p. 3.1-22) and the total thickness of unconsolidated sediments is about 600 m (Dames & Moore, 1991, p. 3.1-2).

Both sites are in the Mojave Desert (Spaulding and others, 1983, p. 261), one of the most arid regions of the United States. Mean annual precipitation at Beatty, Nev., is 12.8 cm on the basis of U.S. Weather Bureau records collected from 1931 to 1989. Precipitation at the burial site in the Amargosa Desert is about 75 percent of that measured at Beatty on the basis of data collected at the site from 1981 to 1989. Mean annual precipitation at Needles, Calif., is 11.7 cm on the basis of U.S. Weather Bureau records from 1931 to 1990.

CHLORIDE PROFILES

Amargosa Desert Site

Chloride concentrations in the unsaturated sediments near the waste-burial site in the Amargosa Desert south of Beatty, Nev., were determined from core samples obtained from three test holes. The first test hole (IB-1; instrument borehole described by Fischer, 1992, p. 18) is about 50 m south of the southwest corner of the waste-burial area (fig. 2). The hole was drilled using the ODEX air hammer method (Fouty, 1989, chap. 3, p. 5; the drilling method is described by Hammermeister and others, 1985). Core samples were taken at depths between 0.69 m and 10.74 m. Chloride concentrations for these samples are reported by Fouty (1989, chap. 3, appendix 2). A chloride concentration in pore water for each sample was calculated from a volumetric water content determined from gravimetric water content and an assumed bulk density of 2.04 g/cm³ (Fouty, 1989, chap. 3, p. 5). Because this value exceeds bulk densities reported by Fischer (1992, p. 20-21), volumetric water content and chloride concentration in pore water were recalculated for each sample using the average bulk density for lithologic units described by Fischer (1992, p. 20).

The equation used to calculate chloride concentrations in pore water is:

$$C_{pw} = (C_s \cdot \rho_b) / (\Theta_v)$$
 (1)

where

C_{pw} is chloride concentration in pore water, in mass per volume of pore water;

C_s is chloride mass in sediment, in mass per mass of sediment;

 ρ_b is bulk density, in mass of sediment per unit volume of bulk sample; and

 Θ_{v} is volumetric water content in volume of water per unit volume of bulk sample.

Equation (1) is the same as dividing C_s with the gravimetric water content (Θ_g) because:

$$\Theta_{g} = \Theta_{v} (\rho_{w} / \rho_{b}), \qquad (2)$$

where

 ρ_w is water density, in mass of water per unit volume and is assumed to be 1 g/cm³.

Values used to calculate chloride concentration in pore water at each sample depth are listed in table 1. Chloride concentrations in pore water listed in table 1 are greater than those listed by Fouty (1989, chap. 3, appendix 2) because Fouty used the volumetric water content yet did not use the bulk density term in equation (1). For example, the maximum chloride concentration in table 1 is 9,000 mg/L at a depth of 2.29 m, whereas the maximum chloride concentration reported by Fouty is 4,400 mg/L at the same depth.

Chloride concentrations were determined in core samples collected from two additional test holes (UZB-1 and UZB-2) drilled about 50 m south of IB-1 (fig. 2). Test hole UZB-1 was drilled in November, 1992, and test hole UZB-2 was drilled in September, 1993. The holes are 6 m apart. Both were drilled using the ODEX air hammer method. Core samples were collected every 3 m in UZB-1 between the depths of 2.5 m and 20 m, and every 12 m in UZB-2 between the depths of about 26 m and 84 m. Core samples of surficial deposits were collected to a depth of 1 m next to UZB-1 during April, 1994.

Bulk density and volumetric water content were determined for each sample. Sediment samples were dry sieved for particle-size distribution prior to chloride analyses. The analyses were performed on the less-than-2-mm size fraction, except whole samples were used for the near-surface samples collected next to UZB-1. Chloride concentrations were determined for each sample by adding three parts of water to one part of sediment by weight, and occasionally shaken during a 24 hour period (Warren W. Wood, U.S. Geological Survey, Reston, Va., written commun., 1994). Chloride concentration in the extracted water was determined using ion chromatography. Chloride concentrations from these samples are listed also in table 1. Chloride concentrations of samples from all three test holes are shown in figure 3.

Chloride concentrations in the pore water of surficial sediments (less than 0.5 m) are less than 50 mg/L. Concentrations increase rapidly from 0.5 to 2.3 m where the chloride concentration peaks at 9,000 mg/L. Chloride concentrations then decrease to a depth of 10 m. Below a depth of 10 m, the chloride concentration in pore water is less than 50 mg/L. This concentration is less than the 79 mg/L of chloride in ground water sampled from nearby well MR3 (fig. 2).

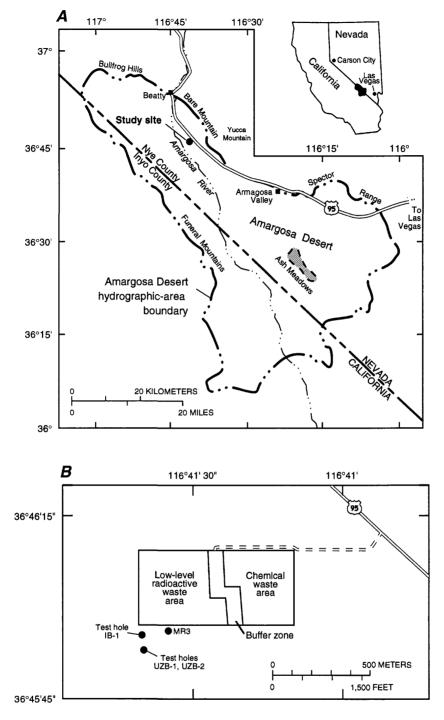


Figure 2. Location of study site next to burial site for low-level radioactive waste in Amargosa Desert hydrographic area (*A*), and location of test holes IB-1, UZB-1 and UZB-2, and monitoring well MR3 in relation to burial site (*B*). Modified from Fischer (1992, fig. 1).

Table 1. Chloride concentrations in samples collected from three test holes next to burial site for low-level radioactive waste, Amargosa Desert, Nevada

[Abbreviations: $\mu g/g$, microgram per gram; g/cm^3 , gram per cubic centimeter; cm^3/cm^3 , cubic centimeter per cubic centimeter, mg/L, milligram per liter]

Depth below land surface ¹ (meters)	Chloride mass per mass of dry sediment ² (µg/g)	Bulk density ³ (g/cm ³)	Volumetric water content ⁴ (cm ³ /cm ³)	Chloride concentration in pore water ⁵ (mg/L)	· Source ⁶
0.0-0.08	0.69	1.57	0.026	42	d
0.08-0.15	.87	1.47	.079	16	d
0.15-0.23	.67	1.50	.080	13	d
0.23-0.30	1.2	1.70	.072	28	d
0.53-0.61	2.4	1.79	.049	88	d
0.69	10	1.46	.032	460	a
0.84-0.91	22	1.83	.045	890	d
1.14	19	1.67	.043	740	a
1.75	132	1.67	.034	6,500	a
2.29	224	1.76	.044	9,000	a
2.51	356	1.76	.087	7,200	a
2.51-2.59	275	1.81	.113	4,400	b
3.05	400	1.72	.102	6,700	a
3.28	357	1.72	.090	6,800	a
3.50	228	1.72	.059	6,600	a
4.27	275	1.72	.083	5,700	a
4.42	266	1.72	.076	6,000	a
5.62-5.70	150	1.63	.084	2,900	b
5.94	277	1.63	.118	3,800	a
6.55	286	1.48	.109	3,900	a
7.31	141	1.48	.071	2,900	a
7.77	120	1.48	.070	2,500	a
8.85-8.93	37	1.72	.080	800	b
9.14	26	1.72	.053	840	a
9.37	25	1.72	.048	900	a
10.59	7.1	1.70	.048	250	a
10.74	7.9	1.70	.045	300	a
11.63-11.70	2.6	2.03	.099	53	b
14.87-15.03	2.5	1.34	.118	28	b
17.75-17.83	1.2	1.82	.092	24	ь
20.80-20.88	1.6	1.79	.105	27	b
36.50-36.58	1.7	2.02	.162	21	c
48.03-48.11	3.3	1.74	.116	50	c
60.16-60.24	3.6	1.91	.142	48	c
72.41-72.49	2.5	1.70	.117	36	c
84.62-84.70	2.9	1.89	.138	40	c
112				79	e

Footnotes on next page.

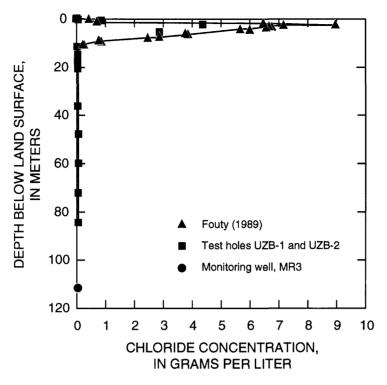


Figure 3. Chloride concentrations in pore water of unsaturated sediments next to burial site for low-level radioactive waste, Amargosa Desert, Nevada. Location of test holes is shown in figure 2.

Footnotes for table 1:

- ¹ Sample interval not reported by Fouty (1989); depth to ground water is used for water sample collected from well MR3.
- ² Mass of chloride per unit mass of sediment rounded to two significant figures to 99 micrograms per gram; rounded to nearest whole number when greater than 100 micrograms per gram.
- ³ Bulk density for samples from source "a" (Fouty, 1989) are from Fischer (1992, p. 21). Bulk density for samples from other sources determined for each sample.
- ⁴ Volumetric water content for samples from source "a" (Fouty, 1989) corrected to bulk density from Fischer (1992, p. 21).
 - ⁵ Rounded to two significant figures.
 - ⁶ Sources of chloride analyses. Location of test holes shown in figure 2.
 - a. Fouty, 1989, appendix 2: test hole IB-1; drilled July 1986.
 - b. Test hole UZB-1; drilled November 1992.
 - c. Test hole UZB-2; drilled September 1993.
 - d. Shallow hand-dug hole next to UZB-1; cored April 1994.
 - e. Water sample from well MR3; sampled August 1989.

Ward Valley Site

Chloride concentrations in the unsaturated sediments near the proposed waste-burial site in Ward Valley were determined from core samples obtained from six test holes (US Ecology, Inc., 1989, appendices 2500.A and 2600.A). Test holes are numbered GB-1 through GB-6 (fig. 4). Two methods were used to determine chloride concentrations. A majority of the analyses are from U.S. Environmental Protection Agency test method 300.0, whereby 10 g of sample was mixed with 100 ml of deionized water (US Ecology, Inc., 1989, appendix 2500.A, p.13). Fewer analyses are from U.S. Environmental Protection Agency, Extraction Procedure Toxicity Test, whereby one part of sample was mixed with four parts of deionized water by weight, shaken for 6 hours during the first day and then shaken for 6 hours 7 days later (US Ecology, Inc., 1989, appendix 2600.A, p. 29).

Bulk density and volumetric water content were not determined from the same sample intervals used to determine chloride concentrations. However, bulk density and volumetric water content were determined from selected core samples collected from the same holes (US Ecology, Inc., 1989, appendix 2420.B). Bulk density and volumetric water content for the nearest sample were used to calculate chloride concentration in pore water using equation (1).

Chloride concentrations in pore water are listed for test holes GB-1 through GB-6 in table 2. Of interest is the chloride concentration of 14,000 mg/L for the uppermost sample in GB-1 (0 to 0.3 m depth). This concentration is much greater than chloride concentrations in surficial samples (0 to 0.3 m depth) at the other five test holes, and is similar to the peak concentration found at 2.4 to 2.9 m depth in test hole GB-2 (table 2). The much greater concentration of chloride found near the surface in test hole GB-1 is unexplained, however, below a depth of 3 m, chloride concentrations in pore water in test hole GB-1 are nearly the same as those in test hole GB-2 (fig. 5). Concentrations below a depth of 3 m range from 4,700 mg/L to 6,800 mg/L in GB-1, and from 4,000 mg/L to 9,200 mg/L in GB-2. Chloride concentrations are less in test hole GB-4 (fig. 5) and below a depth of 3 m, concentrations range from 2,300 mg/L to 6,200 mg/L. Concentrations below a depth of 10 m are between 4,400 mg/L and 8,200 mg/L in test hole GB-2 and 2,300 mg/L and 4,700 mg/L in test hole GB-4. Chloride concentrations from samples in the other three test holes are from too sparse sample intervals to be useful.

The concentrations below a depth of 10 m are greater than those found at the Amargosa Desert site (compare figs. 3 and 5), indicating that considerably more chloride is present in the sediments between the depths of 10 m and 30 m.

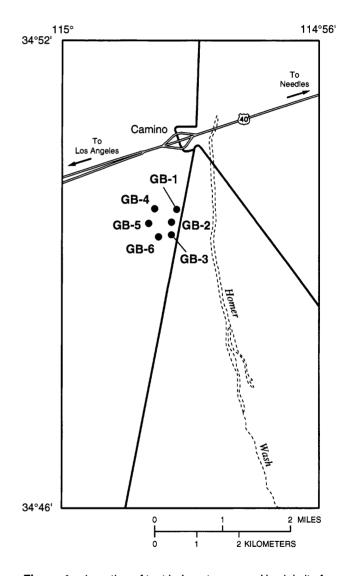


Figure 4. Location of test holes at proposed burial site for low-level radioactive waste, Ward Valley, California. Modified from US Ecology, Inc. (1989, fig. 2420.B-4).

Table 2. Chloride concentrations in samples collected from six test holes at proposed burial site for low-level radioactive waste, Ward Valley, California¹

[Abbreviations: μ g/g, microgram per gram; g/cm³, gram per cubic centimeter; cm³/cm³, cubic centimeter per cubic centimeter, mg/L, milligram per liter]

Depth below land surface (meters)	Chloride ² mass per mass of dry sediment (µg/g)	Bulk ³ density (g/cm ³)	Volumetric ⁴ water content (cm ³ /cm ³)	Chloride ⁵ concentration in pore water (mg/L)	Source ⁶
		Tes	t hole GB-1		
0-0.3	⁷ 252	1.65	0.03	14,000	ь
0.3	220	1.65	.03	12,000	a
0.8-0.9	243	1.65	.03	13,000	b
3.7-4.1	254	1.65	.07	6,000	b
5.2-5.5	246	2.02	.09	5,500	b
6.7-7.3	⁷ 238	1.79	.064	6,700	b
8.2-8.5	228	1.79	.06	6,800	b
9.1-9.3	159	1.79	.06	4,700	b
13.4	180	1.91	.06	5,700	a
		Tes	t hole GB-2		
0.3	2	1.83	.015	240	b
2.4-2.9	420	1.83	.05	15,000	a
3.7-3.8	250	1.83	.05	9,200	a
5.0-5.2	140	1.81	.029	8,700	a
8.7-8.8	180	1.63	.072	4,100	a
9.1-9.3	123	1.63	.05	4,000	b
13.4	160	1.63	.051	5,100	a
15.4-15.6	210	1.63	.05	6,800	a
15.8-16.5	177	1.63	.05	5,800	b
16.9-18.3	180	1.63	.05	5,900	a
18.3-18.4	240	1.63	.05	7,800	a
21.9-22.6	136	1.63	.05	4,400	b
24.4-24.5	200	1.63	.054	6,000	a
27.4-27.6	190	1.63	.05	6,200	a
29.9-30.5	156	1.63	.05	5,100	b
30.8-30.9	250	1.63	.05	8,200	a
		Tes	t hole GB-3		
0.3	3	1.78	.04	130	b

Table 2. Chloride concentrations in samples collected from six test holes at proposed burial site for low-level radioactive waste, Ward Valley, California ¹—Continued

Depth below land surface (meters)	Chloride ² mass per mass of dry sediment (µg/g)	Bulk ³ density (g/cm ³)	Volumetric ⁴ water content (cm ³ /cm ³)	Chloride ⁵ concentration in pore water (mg/L)	Source ⁶
		Tes	t hole GB-4		
0.3	6	1.89	.05	230	a
1.4-1.5	39	1.89	.08	920	a
2.1-2.3	310	1.89	.08	7,300	a
6.2-6.4	200	1.89	.08	4,700	a
9.3-9.4	230	1.89	.07	6,200	a
13.9-14.0	100	1.89	.06	3,200	a
16.9-18.3	84	1.89	.05	3,200	a
19.8-20.0	120	1.89	.05	4,500	a
22.9-23.0	150	1.89	.06	4,700	a
27.4-27.9	87	1.89	.07	2,300	a
30.8-31.2	120	1.89	.06	3,800	a
		Tes	t hole GB-5		
0.3	2	1.83	0.02	180	a
5.2-5.6	163	1.52	.05	5,000	b
6.2-6.4	205	1.52	.049	6,400	b
13.4	110	1.83	.09	2,200	a
		Tes	t hole GB-6		
0.3	20	1.83	.06	610	a
6.7-7.3	⁷ 276	1.67	.086	5,400	b
13.4	72	1.99	.06	2,400	a

¹ Location of test holes shown in figure 4.

² Mass chloride per unit mass of sediment rounded to nearest microgram per gram.

³ Values based on four measurements in test hole GB-1 (depths of 2.3, 4.6, 7.8, and 12.2 meters); three in test hole GB-2 (depths of 0.8, 6.7, and 8.7 meters); one in test hole GB-3 (depth of 0.6 meter); and one in test hole GB-4 (depth of 29 meters); three in test hole GB-5 (depths of 0.9, 2.3, and 21.3 meters); and three in test hole GB-6 (depths of 0.6, 2.3, and 9.1 meters). Values from US Ecology, Inc. (1989, table 2420.B-7).

⁴ Rounded to two significant figures when nearest volumetric moisture content from core sample greater than 0.6 meters from depth of chloride sample or when two nearest samples are averaged.

⁵ Rounded to two significant figures.

⁶ Sources of chloride analyses.

a. US Ecology, Inc. (1989, fig. 2500.A-12); chloride concentration determined using U.S. Environmental Protection Agency test method 300.0.

b. US Ecology, Inc. (1989, table 2600.A-14); chloride concentration determined using U.S.Environmental Protection Agency, Extraction Procedure Toxicity Test.

⁷ Chloride concentration is an average of two analyses.

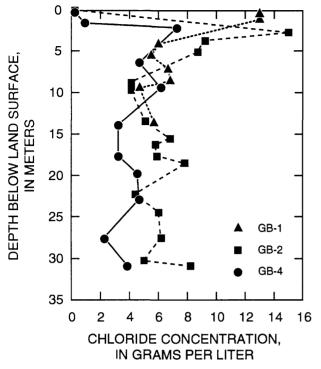


Figure 5. Chloride concentrations in pore water of unsaturated sediments at proposed burial site for low-level radioactive waste, Ward Valley, California. Location of test holes is shown in figure 4.

CHLORIDE MASS BALANCE

Chloride profiles in the unsaturated sediments at both sites were used to estimate the time needed to accumulate chloride in the sediments (referred to as chloride age) and to estimate downward percolation rates (water fluxes). Chloride concentrations in pore water of unsaturated sediments have been used to estimate water fluxes in semiarid and arid regions and when below the zone affected by plants, the rates have been equated to ground-water recharge rates (Allison and others, 1985; Phillips and others, 1988; Scanlon, 1991: Allison and others, 1994; and Phillips, 1994).

The time needed to accumulate chloride in the sediments above a given depth can be estimated by dividing the mass of chloride above that depth by the atmospheric chloride deposition at the surface, and is given as (Phillips and others, 1988, p. 1882):

$$t_n = \sum_{i=1}^{n} C_i z_i / C_o P$$
, (3)

where

t_n is time needed to accumulate mass of chloride in top n depth intervals, in years;

C_i is chloride mass per unit volume of sediment in grams per cubic centimeter measured in depth interval z_i in centimeters;

C_o is chloride mass per unit volume of precipitation, including dry fallout, in grams per cubic centimeter; and

P is annual volume of precipitation per unit area, in centimeters per year.

The water flux can be estimated from chloride profiles by the following equation (Allison and others, 1985):

$$q_w = C_0 P/C, \qquad (4)$$

where

q_w is volumetric water flux, in cubic centimeters per year per square centimeter; and

C is chloride concentration in pore water measured below zone affected by evapotranspiration, in grams per cubic centimeter.

These equations are based on assumed steady, uniform downward flow of water (no change in volumetric water content with time and negligible preferential flow) and that chloride moves with water (negligible hydrodynamic dispersion of the chloride). Other assumptions include:

- Only source of chloride is from atmospheric deposition (wet precipitation plus dry deposition);
- Atmospheric deposition of chloride is constant through time;
- Land surface is unchanging (neither aggrading nor degrading); and
- Chloride concentration in pore water below the root zone is in equilibrium with the flux of chloride at land surface.

The accuracy of the chloride mass-balance method in estimating chloride ages and percolation rates (and hence, recharge rates) at a particular location depends on how well the assumptions used in the equations match the field conditions. Dispersion, anion exclusion (James and Rubin, 1987, and Gvirtzman and others, 1986) and preferential flow (Stephens, 1994) can result in chloride being transported more rapidly and hence, water movement being more rapid than would be estimated from the equations.

More rapid flow through sediment-filled fissures has been documented by Scanlon (1992a) in the Hueco Bolson of Texas. However, data collected at several locations in the southwestern United States indicate that preferential flow is not a dominant transport process in undisturbed sediments at relatively flat sites (Phillips, 1994, p. 19).

In a semiarid region in New Mexico and an arid region in Texas, tritium, a radioactive isotope of hydrogen, has migrated deeper into the sediments than chlorine-36, a radioactive isotope of chlorine (Phillips and others, 1988, and Scanlon, 1992b). The greater depth of water movement in relation to chlorine-36 at these sites is attributed to vapor phase movement of water and indicates that water fluxes estimated from chloride mass balance will be less than the actual water flux (because of downward vapor flow) in such regions (Scanlon, 1991, p. 141). Thermally driven downward vapor density gradients have been computed seasonally to a depth of 12 m at the Amargosa Desert site (Fischer, 1992, table 5).

Changes in precipitation and atmospheric chloride deposition through time may also affect the estimates of chloride ages and percolation rates. A wetter and cooler climate was present in the northern Mojave Desert during the late Pleistocene, from about 30,000 to 18,000 years ago (Spaulding, 1985, p. 50). During glacial maximum (about 18,000 years ago), average annual precipitation was about 30 to 40 percent greater, and average annual temperature was about 6° to 7°C lower than present. This wetter and cooler climate may have resulted in greater percolation rates than those estimated from present climatic conditions, although the effect of the wetter climate on atmospheric chloride deposition is unknown.

The present-day arid climate in the Mojave Desert has been prevalent for the last 10,000 years, although a relatively rapid decline in the water level over the past 20,000 years at Devils Hole near the regional ground-water discharge area in southern Amargosa Desert indicates the onset of drying may have occurred earlier (Szabo and others, 1994, p. 59). The arid climate during the last 8,000 years in parts of the Mojave Desert has been interrupted with short periods of wetter- than-present-day conditions, as documented in the Mojave River drainage basin west of the proposed Ward Valley site (Enzel and others, 1994).

The validity of the assumptions used to estimate chloride ages and downward percolation rates at the two sites is difficult to quantify, particularly for the long time periods that are needed to accumulate chloride found in the sediments from atmospheric deposition. Still, the chloride profiles at both sites can provide useful information on long-term percolation rates (water fluxes) and chloride ages at both sites.

ESTIMATES OF CHLORIDE AGES AND PERCOLATION RATES

Amargosa Desert Site

Cumulative chloride, which is the summation term in equation (4), was calculated from the chloride profile listed in table 1. Cumulative chloride is used to estimate the time needed to accumulate chloride (referred to as chloride age) to selected depths. Chloride age can be interpreted as the age of the water at the depth to which chloride has accumulated. Chloride concentrations were converted from mass of chloride per mass of sediment (µg/g) to mass of chloride per volume of sediment (µg/cm³) by multiplying the concentration with bulk density. Average bulk densities reported by Fischer (1992, p. 20) were used to convert chloride concentrations from samples collected in test hole IB-1 and reported by Fouty (1989, chap. 3, appendix 2), whereas the bulk density of each sample was used to convert chloride concentrations analyzed from samples collected in test holes UZB-1 and UZB-2.

Cumulative chloride mass was calculated assuming an average chloride concentration for each depth interval. Depth intervals were determined two ways. For samples where only a specific depth is listed (primarily samples below a depth of 0.69 m), chloride concentration at each depth was assumed to represent the average chloride for a depth interval between the midway points to adjacent samples. For example, chloride concentrations are reported for depths of 1.14 m, 1.75 m, and 2.29 m in table 1. The chloride concentration at a depth of 1.75 m was assumed to represent the chloride concentration for the depth interval from 1.44 m (midway between 1.14 m and 1.75 m) to 2.02 m (midway between 1.75 m and 2.29 m). For surficial samples collected near UZB-1, chloride concentration was linearly interpolated between each depth interval and assumed to represent an average concentration between reported intervals. Cumulative chloride per unit area is listed in table 3.

Table 3. Chloride in selected depth intervals and cumulative chloride in unsaturated sediments next to burial site for low-level radioactive waste, Amargosa Desert, Nevada¹

[Abbreviations: cm, centimeter; $\mu g/g$, microgram per gram; g/cm^3 , gram per cubic centimeter; $\mu g/cm^2$, microgram per square centimeter]

Depth interval meters	Interval length (cm)	Chloride ² mass per mass of dry sediment (µg/g)	Bulk ³ density (g/cm ³)	Chloride ⁴ mass per volume (μg/cm ³)	Chloride in ⁴ depth interval (μg/cm ²)	Cumulative ⁵ chloride (μg/cm²)
0.00008	7.6	0.69	1.57	1.08	8.2	8.2
.08-0.15	7.6	.87	1.47	1.28	9.7	18
.15-0.23	7.6	.67	1.50	1.00	7.6	26
.23-0.30	7.6	1.2	1.70	2.04	15.5	41
.30-0.53	23.	1.8	1.74	3.13	72.0	110
.53-0.61	7.6	2.4	1.79	4.30	32.6	150
.61-0.76	15	10	1.46	14.6	219	360
.76-1.02	26	22	1.83	40.3	1,050	1,400
1.02-1.44	42	19	1.67	31.7	1,330	2,700
1.44-2.02	58	132	1.67	220	12,800	16,000
2.02-2.40	38	224	1.76	394	15,000	31,000
2.40-2.53	13	356	1.76	626	8,150	39,000
2.53-2.80	27	275	1.81	498	13,400	52,000
2.80-3.16	36	400	1.72	688	24,800	77,000
3.16-3.39	23	357	1.72	614	14,100	91,000
3.39-3.88	49	228	1.72	392	19,200	110,000
3.88-4.34	46	275	1.72	473	21,800	132,000
4.34-5.04	70	266	1.72	458	32,000	164,000
5.04-5.80	76	150	1.63	244	18,600	183,000
5.80-6.24	44	277	1.63	452	19,900	202,000
6.24-6.93	69	286	1.48	423	29,200	232,000
6.93-7.54	61	141	1.48	209	12,700	244,000
7.54-8.33	79	120	1.48	178	14,000	258,000
8.33-9.02	69	37	1.72	63.6	4,390	263,000
9.02-9.26	24	26	1.72	44.7	1,070	264,000
9.26-9.98	72	25	1.72	43.0	3,100	267,000
9.98-10.66	68	7.1	1.70	12.1	821	268,000
10.66-11.20	54	7.9	1.70	13.4	725	269,000
11.20-13.31	211	2.6	2.03	5.28	1,110	270,000
13.31-16.38	307	2.5	1.34	3.35	1,030	271,000
16.38-19.32	294	1.2	1.82	2.18	642	271,000
19.32-28.69	937	1.6	1.79	2.86	2,680	274,000
28.69-42.30	1,361	1.7	2.02	3.43	4,670	279,000
42.30-54.13	1,183	3.3	1.74	5.74	6,790	285,000
54.13-66.33	1,220	3.6	1.91	6.88	8,390	294,000
66.33-78.55	1,222	2.5	1.70	4.25	5,190	299,000
78.55-84.66	611	2.9	1.89	5.48	3,350	302,000

Footnotes on facing page.

Estimates of chloride age at the Amargosa Desert site are calculated using an estimated atmospheric chloride deposition of 8.2x10⁻⁶ g/cm²/yr. This value was obtained by multiplying long-term average precipitation of 10 cm/yr (slightly more than the 9 cm/yr average annual precipitation recorded for the period 1981-1989) and an average chloride concentration of precipitation including dry fallout of 0.82×10^{-6} g/cm³ measured at nearby Yucca Mountain, Nev. (C.A. Peters, U.S. Geological Survey, Denver, Colo., written commun., 1992). Estimated chloride age at 1 m is about 170 years; at 3.3 m, it is about 10,000 years; at 10 m, it is about 33,000 years; and at 80 m it is about 37,000 years (table 4). The estimated atmospheric chloride deposition is slightly less than the atmospheric chloride deposition of 1.0x10⁻⁵ g/cm²/yr for the Nevada Test site reported by Phillips (1994, p. 16). Doubling atmospheric chloride deposition to 1.64x10⁻⁵ g/cm²/yr (effectively increasing precipitation to 15 cm/yr and chloride concentration in precipitation and dry fallout to 1.1x10⁻⁶ g/cm³) decreases the estimated chloride ages by a factor of two. The two atmospheric chloride deposition values encompass a reasonable range since the climate was wetter in the past. Thus, a range in estimated chloride ages is listed in table 4 and is based on the two atmospheric chloride deposition values. Because long-term atmospheric chloride deposition is unknown, these estimated ages are only approximate.

The relatively small concentrations of chloride in the sediments below a depth of 10 m indicate that in the past, the sediments were either flushed with dilute water or the sediments never contained much chloride. Either process implies that sufficient water was available in the past to keep chloride from accumulating in the sediments. Since the time water flushed the sediments, chloride has been accumulating in the upper 10 m. When chloride began accumulating in the near surface sediments is not known for certain. The time period of 16,000 to 33,000 years ago as estimated from chloride age at a depth of 10 m (table 4) corresponds to a period when climate at the site was both wetter and cooler, and more precipitation likely fell on the valley floor. During this period, downward percolation could have been greater than it is now. More frequent flooding of the Amargosa River also may have occurred during this period. Deposition of coarse gravel deposits at the site is influenced more by down-valley surface flow associated with the Amargosa River than by lateral infilling from the bounding alluvial fans (Nichols, 1987, p. 8). Perhaps a large flood that deposited the near-surface gravels throughout much of the site area (Fischer, 1992, p. 19) may have been sufficient to flush any salts that had accumulated in the sediments.

The rapid decrease in chloride from a depth of about 2 m to 10 m could indicate little or no downward water flow to 10 m has occurred since the sediments were flushed. Measurements of water content, water potential, and temperature in the sediments have been taken to a depth of 13 m since 1986 and water potential and temperature measurements have been taken between the depths of 13 and 48 m, since 1993. Water potential and vapor density increase downward between the depths of 12 and 48 m indicating water

Footnotes for table 3:

¹ Average chloride mass per mass of sediment assumed for each depth interval based on analyses of core samples collected from test holes UZB-1, UZB-2, and from analyses reported by Fouty (1989). Chloride mass for specific depths and source listed in table 1.

² Mass of chloride per unit mass of sediment rounded to two significant figures to 99 micrograms per gram; rounded to nearest whole number when greater than 100 micrograms per gram.

³ Bulk density from table 1.

⁴Rounded to three significant figures.

⁵ Rounded to two significant figures to 10,000 micrograms per square centimeter; rounded to nearest 1,000 when greater than 10,000 micrograms per gram.

Table 4. Estimated chloride age from accumulated chloride for indicated depth in unsaturated sediments next to burial site for low-level radioactive waste, Amargosa Desert, Nevada

[Abbreviation: µg/cm², microgram per square centimeter]

Depth below land surface meters	Cumulative chloride ¹ (μg/cm²)	Estimated chloride ² age years
0.08	8.2	0.5-1.0
.15	18	1.1-2.2
.30	41	2.5-5.0
.61	150	9.1-18
1.02	1,400	85-170
2.02	16,000	980-2,000
3.16	77,000	4,700-9,400
5.04	164,000	10,000-20,000
7.54	244,000	15,000-30,000
9.98	267,000	16,000-33,000
42.30	285,000	17,000-35,000
84.66	302,000	18,000-37,000

¹ From table 3.

movement both as liquid and vapor is upward (Prudic and Striegl, 1994). Water potentials increase from -3.5×10^6 Pa at a depth of 12 m to -0.9×10^6 Pa at a depth of 48 m. Vapor density increases from $18.6 \, \mu \text{g/cm}^3$ at 12 m to $21.4 \, \mu \text{g/cm}^3$ at 48 m in response to a temperature increase of 0.06°C/m . Water potentials, temperatures and vapor densities change seasonally in the zone of chloride accumulation (Fischer, 1992, p. 45). Additionally, moisture content changes have been observed only in the uppermost meter in response to precipitation (Fischer, 1992, p. 23), and correspond to an interval of little chloride accumulation (table 1).

A downward percolation rate of about 0.2 cm/yr is calculated from the chloride profile assuming: (1) a chloride concentration in pore water of 50 mg/L $(5x10^{-5} \text{ g/cm}^3)$ for sediments below a depth of 10 m (interval not presently affected by evapotranspiration); (2) average annual precipitation of 10 cm/yr; and (3) a chloride concentration in precipitation and dry fallout of $0.82x10^{-6} \text{ g/cm}^3$. If water potential and vapor den-

sity gradients have been upward since the sediments were deposited, than equation (4) does not apply because the assumption of steady, uniform downward flow is invalid. If the sediments were once flushed with water by downward percolation of precipitation during the late Pleistocene and the sediments have been slowly drying in response to an arid climate, then the estimated percolation rate may represent downward flow during the late Pleistocene. If, however, the chlorides in the sediments have been flushed because of flooding from the Amargosa River, then again the estimate would not apply because the assumption that chloride is from atmospheric deposition would be invalid.

The estimated downward percolation rate at a depth of 2.29 m (depth of maximum chloride concentration; table 1) is 0.009 cm/yr. Although estimated rates in the upper 10 m are likely affected by evapotranspiration, percolation rates of less than 0.02 cm/yr are estimated between 1 m and 10 m depths. These low rates correspond to rates calculated for the Amargosa Desert site by Phillips (1994, p. 21). Furthermore, Phillips compared rates estimated at the Amargosa site to five other sites in the deserts of the southwestern United States, and noted a similar pattern at all sites of relatively high rates prior to 16,000 years ago; rapid decrease in rates between 16,000 and 13,000 years ago; and relatively constant and low rates since 12,000 years ago. The marked decrease in flow rates is attributed to a dramatic decrease in water caused by climate change.

Ward Valley Site

Cumulative chloride was calculated from the chloride profiles in test holes GB-2 and GB-4 listed in table 2. Chloride concentrations were converted from mass of chloride per mass of sediment (µg/g) to mass of chloride per volume of sediment (µg/cm³) by multiplying the concentration with bulk density from table 2. Cumulative chloride was calculated assuming an average chloride concentration for each depth interval. Chloride concentration was linearly interpolated between each reported depth interval listed in table 2 and assumed to represent an average concentration between sample intervals. Cumulative chloride for the selected depth intervals are listed in table 5. Cumulative chloride at a depth of about 30 m is about 3 to 4 times greater than that estimated at the Amargosa Desert site (compare tables 3 and 5).

 $^{^2}$ Estimated chloride ages rounded to two significant figures from equation (3) assuming range in annual volume of precipitation per unit area of 10 to 15 centimeters per year and range in chloride mass per unit volume of precipitation including dry fallout of 0.82×10^{-6} to 1.1×10^{-6} gram per cubic centimeter.

Estimates of chloride ages are calculated assuming atmospheric chloride deposition is of 1.64x10⁻⁵ g/cm²/yr. This value was obtained by multiplying long-term average precipitation of 15 cm/yr (about 130 percent of the mean annual precipitation of 11.7 cm/yr recorded from 1931 to 1990 at Needles, Calif.; mean annual precipitation at the Ward Valley site is unknown but is presumably greater than that at Needles because it is at a higher altitude), and an average chloride concentration of precipitation including dry fallout of 1.1x10⁻⁶ g/cm³ (maximum chloride concentration used in estimating chloride ages at the

Amargosa Desert site; actual values have not been measured at the Ward Valley site). Chloride concentration from test holes GB-2 and GB-4 are used. Data in the upper meter are sparse. Estimated chloride age at a depth of 0.3 m is from about 7 to 20 years; at a depth of 3 m, it is about 8,000 years; at a depth of about 9 m, it is about 20,000 years; and at a depth of 31 m, it is between 52,000 and 58,000 years (table 6). The latter two estimates are only approximate because of the uncertainty in precipitation and atmospheric chloride deposition for the period 15,000 to 58,000 years ago.

Table 5. Chloride in selected depth intervals and cumulative chloride in unsaturated sediments at proposed burial site for low-level radioactive waste, Ward Valley, California

[Abbreviations: cm, centimeter; $\mu g/g$, microgram per gram; g/cm^3 , gram per cubic centimeter; $\mu g/cm^2$, microgram per square centimeter.]

Depth ¹ interval meters	interval length (cm)	Chloride ² mass per weight of sediment (µg/g)	Bulk ³ density (g/cm ³)	Chloride ⁴ mass per volume (μg/cm ³)	Chloride in ⁴ depth interval (μg/cm ²)	Cumulative ⁵ chloride (μg/cm²)
			Test hole GB	-2		
0.0- 0.3a	30	2	1.83	3.66	110	110
.3- 2.4	210	235	1.83	430	90,300	90,400
2.4- 2.9a	50	420	1.83	769	38,400	129,000
2.9- 3.7	80	335	1.83	613	49,000	178,000
3.7- 3.8a	10	250	1.83	458	4,580	182,000
3.8- 5.0	120	195	1.83	357	42,800	225,000
5.0- 5.2a	20	140	1.81	253	5,070	230,000
5.2-8.7	350	160	1.73	277	96,900	327,000
8.7- 8.8a	10	180	1.63	293	2,930	330,000
8.8-9.1	30	150	1.63	245	7,350	337,000
9.1-9.3a	20	123	1.63	200	4,000	341,000
9.3-15.4a	610	160	1.63	261	159,000	500,000
15.4-15.6a	20	210	1.63	342	6,850	507,000
15.6-16.9a	130	177	1.63	289	37,600	545,000
16.9-18.3a	140	180	1.63	293	41,100	586,000
18.3-18.4a	10	240	1.63	391	3,910	590,000
18.4-21.9	350	188	1.63	306	107,000	697,000
21.9-22.6a	70	136	1.63	222	15,500	712,000
22.6-24.4	180	170	1.63	277	49,900	762,000
24.4-24.5a	10	200	1.63	326	3,260	766,000
24.5-27.4	290	195	1.63	318	92,000	858,000
27.4-27.6a	20	190	1.63	310	6,190	864,000
27.6-29.9	230	170	1.63	277	63,700	927,000
29.9-30.8a	90	156	1.63	254	22,900	950,000
30.8-30.9a	10	250	1.63	408	4,080	954,000

Table 5. Chloride in selected depth intervals and cumulative chloride in unsaturated sediments at proposed burial site for low-level radioactive waste, Ward Valley, California—Continued

Depth ¹ interval meters	Interval length (cm)	Chloride ² mass per weight of sediment (µg/g)	Bulk ³ density (g/cm ³)	Chloride ⁴ mass per volume (μg/cm ³)	Chloride in ⁴ depth interval (μg/cm ²)	Cumulative ^t chloride (μg/cm²)
	·		Test hole GB	-4		
0.0- 0.3a	30	6	1.89	11.3	340	340
.3- 1.4	110	22	1.89	41.6	4,570	4,910
1.4- 1.5a	10	39	1.89	73.7	737	5,650
1.5- 2.1	60	174	1.89	329	19,700	25,300
2.1- 2.3a	20	310	1.89	586	11,700	37,000
2.3- 6.2	390	255	1.89	482	188,000	225,000
6.2- 6.4a	20	200	1.89	378	7,560	233,000
6.4- 9.3	290	215	1.89	406	118,000	351,000
9.3- 9.4a	10	230	1.89	435	4,350	355,000
9.4-13.9	450	165	1.89	312	140,000	495,000
13.9-14.0a	10	100	1.89	189	1,890	497,000
14.0-16.9	290	92	1.89	174	50,400	547,000
16.9-18.3a	140	84	1.89	159	22,200	569,000
18.3-19.8	150	102	1.89	193	29,000	598,000
19.8-20.0a	20	120	1.89	227	4,540	603,000
20.0-22.9	290	135	1.89	255	74,000	677,000
22.9-23.0a	10	150	1.89	284	2,840	680,000
23.0-27.4	440	118	1.89	223	98,100	778,000
27.4-27.9a	50	87	1.89	164	8,200	786,000
27.9-30.8	290	104	1.89	197	57,000	843,000
30.8-31.2a	40	120	1.89	227	9,070	852,000

¹ An average chloride mass per mass of sediment is assumed for each depth interval. Chloride mass per mass of sediment for depth intervals followed with "a" are from intervals listed in table 2. Chloride mass per mass of sediment for remaining intervals are based on a linear interpolation between adjacent intervals.

The estimated percolation rates at the Ward Valley site are relatively uniform and low since at least the late Pleistocene. A downward percolation rate of about 0.003 cm/yr for test holes GB-1 and GB-2, and 0.005 cm/yr for GB-4 is calculated below a depth of 10 m from chloride profiles assuming a chloride concentration in pore water of 5,200 mg/L (5.2x10⁻³ g/cm³) in

test hole GB-1, 6,000 mg/L (6.0x10⁻³ g/cm³) in test hole GB-2, and 3,500 mg/L (3.5x10⁻³ g/cm³) in test hole GB-4, and an atmospheric chloride deposition of 1.64x10⁻⁵ g/cm²/yr. Because estimated chloride ages are older than 20,000 years for depths below 10 m, these rates likely represent flow during the late Pleistocene.

² Mass of chloride per unit mass of sediment rounded to nearest microgram per gram.

³ Bulk density from table 2.

⁴ Rounded to three significant figures.

⁵ Rounded to two significant figures to 10,000 micrograms per square centimeter; rounded to nearest 1,000 when greater than 10,000 micrograms per gram.

Table 6. Estimated chloride age from accumulated chloride for indicated depth in unsaturated sediments at proposed burial site for low-level radioactive waste, Ward Valley, California

[Abbreviation: µg/cm², microgram per square centimeter]

Depth below land surface meters	nd surface Cumulative chloride (ug/cm²)	
	Test hole GB-2	
0.3	110	6.7
2.9	129,000	7,800
5.2	230,000	14,000
8.8	330,000	20,000
15.6	507,000	31,000
24.5	766,000	46,000
30.9	954,000	58,000
	Test hole GB-4	
0.3	340	21
2.3	37,000	2,300
6.4	233,000	14,000
9.4	355,000	22,000
14.0	497,000	30,000
23.0	680,000	41,000
31.2	852,000	52,000

¹ From table 5

Estimated downward percolation rates at depths of maximum chloride concentrations (0-0.3 m for GB-1; 2.4-2.9 m for GB-2; and 2.1-2.3 m for GB-4, table 2) range from 0.001 cm/yr to 0.002 cm/yr. The estimated ages that corresponds to these rates range from 2,300 years to 7,800 years (table 6). Because of the uncertainty in the estimate of long-term precipitation and atmospheric chloride deposition at the site, the percolation rates are only approximate. However, the relatively uniform rates with depth and between test holes remain. Doubling the atmospheric chloride deposition would only increase the estimated percolation rates and decrease the estimated ages by a factor of two.

Comparison of Ward Valley Site to Amargosa Desert Site

The estimated chloride ages for test holes GB-2 and GB-4 at the Ward Valley site are compared to the estimated chloride ages from the Amargosa Desert site (fig. 6). The estimated chloride ages for the Amargosa site are based on the higher atmospheric chloride deposition of 1.64x10⁻⁵ g/cm²/vr, which produces the lower ages listed in table 4. The estimated ages at the Ward Valley site are nearly the same to a depth of 10 m indicating that chloride in this interval has been accumulating at about the same rate (and presumably, downward percolation is at about the same rate) at both the Amargosa Desert and Ward Valley sites. Below a depth of 10 m, estimated chloride ages at the Ward Valley site increase more rapidly with depth than at the Amargosa Desert site, indicating the sediments near the two test holes at the Ward Valley site did not undergo the same flushing that removed chloride from the deeper profile at the Amargosa Desert site. This also is reflected in the estimate of downward percolation rates, which, for the depth interval of 10 m to 30 m, are about 2 orders of magnitude less than the percolation rate estimated at the Amargosa Desert site.

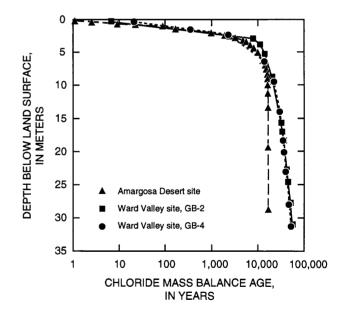


Figure 6. Estimated chloride ages from two chloride profiles at proposed burial site, Ward Valley, California, and estimated chloride ages from a chloride profile next to burial site, Amargosa Desert, Nevada. Estimated chloride ages are based on assumed average annual precipitation of 15 centimeters at both sites, and chloride mass per unit volume of precipitation of 1.1x10⁻⁶ gram per cubic centimeter.

² Estimated chloride ages rounded to two significant figures from equation (3) assuming an annual volume of precipitation per unit area of 15 centimeters per year and a chloride mass per unit volume of precipitation including dry fallout of 1.1x10⁻⁶ gram per cubic centimeter.

SUMMARY AND CONCLUSIONS

Thick unsaturated zones in arid regions are increasingly being sought for the burial of radioactive and other hazardous wastes. Estimating percolation rates of water from precipitation at proposed burial sites is important for site assessment. Chloride profiles in unsaturated sediments are used to show differences and similarities in the rates of percolation at two sites in the Mojave Desert of southern Nevada and southeastern California; one is at an existing burial site for low-level radioactive wastes in the Amargosa Desert, and the other is at a proposed waste-burial site in Ward Valley. The Mojave Desert is one of the most arid regions of the United States.

Chloride concentrations in the pore water of the upper 3 m of unsaturated sediments are similar at both the Amargosa Desert site and the Ward Valley site. At both sites, chloride concentrations increase rapidly to a depth of about 2 to 3 m with peak concentrations of 9,000 to 15,000 mg/L in pore water, respectively. Concentrations decrease below this depth with concentrations at the Amargosa Desert site decreasing to less than 50 mg/L below a depth of 10 m. In contrast, concentrations below the depth of 10 m at the Ward Valley site are considerably greater and are generally between 2,000 mg/L and 8,200 mg/L.

Estimated chloride age (time to accumulate chloride) at a depth of 10 m at the Amargosa Desert site is about 16,000 to 33,000 years assuming a range in atmospheric deposition chloride deposition at land surface of 8.2×10^{-6} to 1.64×10^{-5} g/cm²/yr. Estimated chloride age at the Ward Valley site is similar; the estimated age for a depth of 9 m is about 20,000 years assuming an atmospheric chloride deposition of 1.64×10^{-5} g/cm²/yr. Below a depth of 10 m, however, estimated chloride ages at the Ward Valley site are considerably older because of the greater chloride concentrations found in the sediments at depth.

The relatively low chloride concentrations in the pore water below a depth of 10 m at the Amargosa Desert site could indicate that the sediments were flushed with water in the past. The chloride age of

16,000 to 33,000 years approximates the time when the climate in the area was wetter and cooler (about 30,000 to 18,000 years ago). The wetter and cooler climate could have resulted in deep percolation of water through the sediments from greater precipitation or from more frequent flooding of the Amargosa River. Since that time, however, the sediments probably have been drying slowly in response to an arid climate, and deep percolation of water has been limited to the upper 10 m. This interpretation is consistent with the observed upward water-potential and vapor-density gradients between the depths of 12 and 48 m.

A downward percolation rate of about 0.2 cm/yr is calculated from chloride concentrations below a depth of 10 m. The rate probably is representative of an earlier time during the late Pleistocene when the climate was wetter and cooler.

The greater chloride concentrations below a depth of 10 m at the Ward Valley site indicate the site has not undergone a similar flushing that removed chloride from the deeper sediments. Downward percolation rates estimated for the depth interval from 10 to 30 m range from 3 cm per 1,000 years to 5 cm per 1,000 years assuming an atmospheric chloride deposition 1.64x10⁻⁵ g/cm²/yr. Percolation rates in the upper 3 m of sediments range from 1 cm per 1,000 years to 2 cm per 1,000 years implying relatively uniform rates have persisted at the Ward Valley site since the late Pleistocene.

In conclusion, chloride has been accumulating in the upper 10 m at the two sites in the Mojave Desert for the last 16,000 to 33,000 years and below this depth, either water movement is upward, as indicated by water-potential and vapor-density gradients measured at the Amargosa Desert site, or downward flow is extremely slow (on the order of 3 to 5 cm per 1,000 years), as indicated by chloride concentrations at the Ward Valley site.

REFERENCES CITED

- Allison, G.B., Gee, G.W., and Tyler, S.W., 1994, A review of vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions: Soil Science Society of America Journal, v. 58, p. 63-72.
- Allison, G.B., and Hughes, M.W., 1978, The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer: Australian Journal of Soil Research, v. 16, p. 181-195.
- Allison, G.B., and Hughes, M.W., 1983, The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region: Journal of Hydrology, v. 60, p. 157-173.
- Allison, G.B., Stone, W.J., and Hughes, M.W., 1985, Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride: Journal of Hydrology, v. 76, p. 1-26.
- Dames & Moore, 1991, State of California indemnity selection and low-level radioactive waste facility: Santa Ana, California, Final Environmental Impact Report/Statement SCH 80052308, 3 volumes.
- Enzel, Yehouda, Brown, W.J., Anderson, R.V., McFadden, L.D., and Wells, S.G., 1992, Short-duration Holocene lakes in the Mojave River drainage basins, southern California: Quaternary Research, v. 38, p. 60-73.
- Fischer, J.M., 1992, Sediment properties and water movement through shallow unsaturated alluvium at an arid site for disposal of low-level radioactive waste near Beatty, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 92-4032, 48 p.
- Fouty, Suzanne, 1989, Chloride mass-balance method for determining long-term ground-water recharge rates and geomorphic surface stability in arid and semi-arid regions--Whiskey Flat and Beatty, Nevada: Tucson, University of Arizona, unpublished M.S. thesis, 130 p.
- Gvirtzman, Haim, Ronen, Daniel, and Magaritz, Mordeckai, 1986, Anion exclusion during transport through the unsaturated zone, Journal of Hydrology, v. 87, p. 267-283.
- Hammermeister, D.P., Blout, D.O., and McDaniel, J.C., 1985, Drilling and coring methods that minimize the disturbance of cuttings, core, and rock formation in the unsaturated zone, Yucca Mountain, Nevada: National Water Well Association, Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Denver, Colo., November 1984, Proceedings, p. 507-541.
- James, R.V., and Rubin, Jacob, 1986, Transport of chloride ion in water-unsaturated soil exhibiting anion exclusion: Soil Science Society of America Journal, v. 50, p. 1142-1149.

- Nichols, W.D., 1987, Geohydrology of the unsaturated zone at the burial site for low-level radioactive waste near Beatty, Nye County, Nevada: U.S. Geological Survey Water-Supply Paper 2312, 57 p.
- Phillips, F.M., 1994, Environmental tracers for water movement in desert soils of the American Southwest: Soil Science Society of America Journal, v. 58, p. 15-24.
- Phillips, F.M., Mattick, J.L., Duval, T.A., Elmore, David, and Kubik, P.W., 1988, Chlorine 36 and tritium from nuclear weapons fallout as tracers for long-term liquid movement in desert soils: Water Resources Research, v. 24, n. 11, p. 1877-1891.
- Prudic, D.E. and Striegl, R.G., 1994, Water and carbon dioxide movement through unsaturated alluvium near an arid disposal site for low-level radioactive waste, Beatty, Nevada [abs.]: American Geophysical Union, 1994 spring meeting, Baltimore, Maryland, EOS, v. 75, n. 16, p. 161.
- Scanlon, B.R., 1991, Evaluation of moisture flux from chloride data in desert soils: Journal of Hydrology, v. 128, p. 137-156.
- Scanlon, B.R., 1992a, Moisture and solute flux along preferred pathways characterized by fissured sediments in desert soils: Journal of Contaminant Hydrology, v. 10, p. 19-46.
- Scanlon, B.R., 1992b, Evaluation of liquid and vapor water flow in desert soils based on chlorine 36 and tritium tracers and nonisothermal flow simulations: Water Resources Research, v. 28, n. 1, p. 285-297.
- Szabo, B.J., Kolesar, P.T., Riggs, A.C., Winograd, I.J., and Ludwig, K.R., 1994, Paleoclimatic inferences from a 120,000-yr calcite record of water-table fluctuation in Browns Room of Devils Hole, Nevada: Quaternary Research, v. 41, p. 59-69.
- Spaulding, W.G., 1985, Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada: U.S. Geological Survey Professional Paper 1329, 83 p.
- Spaulding, W.G., Leopold, E.B., Van Devender, T.R., 1983, Late Wisconsin Paleoecology of the American Southwest, in Porter, S.C., ed., Late-Quaternary environments of the United States, Volume 1, The Late Pleistocene: Minneapolis, University of Minnesota Press, p. 259-293.
- Stephens, D.B., 1994, A perspective on diffuse natural recharge mechanisms in areas of low precipitation: Soil Science Society of America Journal, v. 48, p. 40-48.
- US Ecology, Inc., 1989, California low-level radioactivewaste disposal facility—License application: Newport Beach, California, 11 volumes.